XXII. Spacecraft Telemetry and Command

TELECOMMUNICATIONS DIVISION

N67-29163

A. Photon Actuated, Solid State Switch Development, *D. M. Bergens*

1. Introduction

During the past few years JPL has been planning and developing a new generation of telecommunications equipment based on the use of microelectronics. Although commercially available monolithic integrated circuits are satisfactory for many digital and analog spacecraft and operational support equipment applications, certain electronic circuit functions are unique and require custom development. One such function is coupling a signal across an interface while maintaining electrical isolation at the interface.

Signal coupling with electrical isolation is a useful and sometimes indispensible function in the design of electrical or electronic equipment. This function can be achieved by converting electrical energy into another form of energy which serves as the coupling medium. In a transformer or relay, for example, magnetic flux serves as the coupling medium. Transformers and relays are used for isolation in present day equipment, but they are generally less reliable than solid state devices. Also, they are not physically compatible with microelectronic form factors. Acoustic or mechanical force waves in a crystal can serve as a coupling medium, but the transducers are not suited to the needs of microelectronics. Heat can also be used as a coupling medium, but the response time is extremely slow.

Light rays are another means of providing isolation of electrical signals. Light coupling has the advantage of being unilateral, physically compact, and capable of great speed. Until recently, however, the use of light coupling in electronics has been limited due to deficiencies in the light source.

The discovery of the phenomenon of infrared emission from the junction of a foreward biased gallium arsenide diode suggested a light source that might be suitable for microelectronic coupling. The Ga As emission spectrum peaks in the region of 9000 A, where silicon photon sensitivity is greatest. Therefore; if the infrared emission could be efficiently coupled to a silicon phototransistor, a microelectronic, solid state isolation would be achieved.

In April 1963, the components division of the International Business Machines Corporation (IBM) was given a contract by JPL to determine if a practical photon-coupled isolation device of this type could be made. In January 1966, Texas Instruments, Incorporated (TI) was given a contract for development of another photon-actuated isolation device. The remainder of this article will cover these developments.

2. The IBM Development

The IBM contract was for the development of a photon-actuated solid state switch for the precision multiplexing of analog voltages in a spacecraft telemetry system. The 18-mo development is reported in detail in a JPL technical report (Ref. 1). The multiplex switch was an ambitious undertaking as a first effort in photon-coupling. Severe requirements were placed on the silicon detector, which also had to serve as the switch element. Assembly of the switch components on a TO-18 header and a top view of the silicon detector is shown in Fig. 1. Note that the silicon detector is a dual emitter transistor with common base and collector. This configuration was chosen to achieve optimum matching of the transistors for minimum offset voltage, thermal balance, fewer connections, ease of assembly, and compactness. The dual emitter transistor was tailored to meet the difficult requirements of high breakdown, low offset voltage, low leakage current, low on-resistance, and low capacitance between emitters. It also had to be a good light receiver. Various combinations of single or double diffusion and single or double epitaxy were tried in making NPN and PNP detectors. The detector that gave the best trade-off in parameters was a NPN planar device with an epitaxial base. This device was used in assembled switches.

The principal problem encountered during the development was a decrease in photon emission from the Ga As

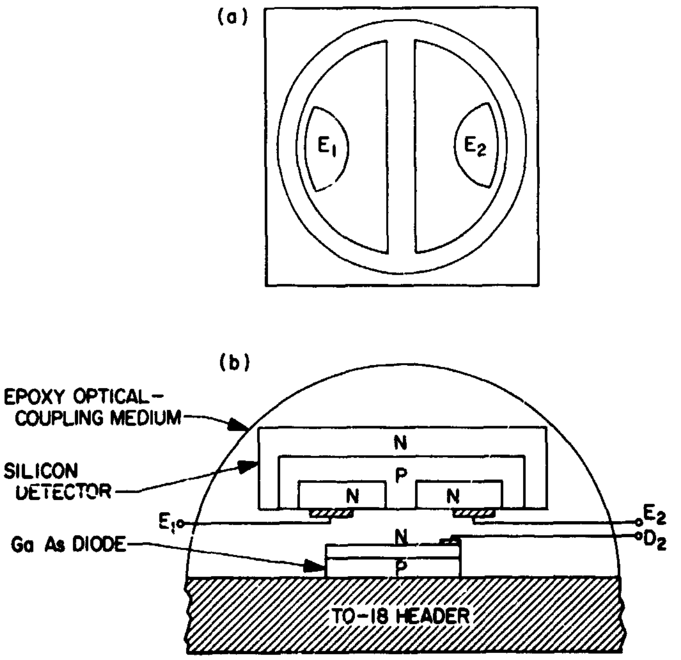

Fig. 1. Multiplex switch: (a) top view of silicon detector; (b) assembly of switch components on a TO-18 header

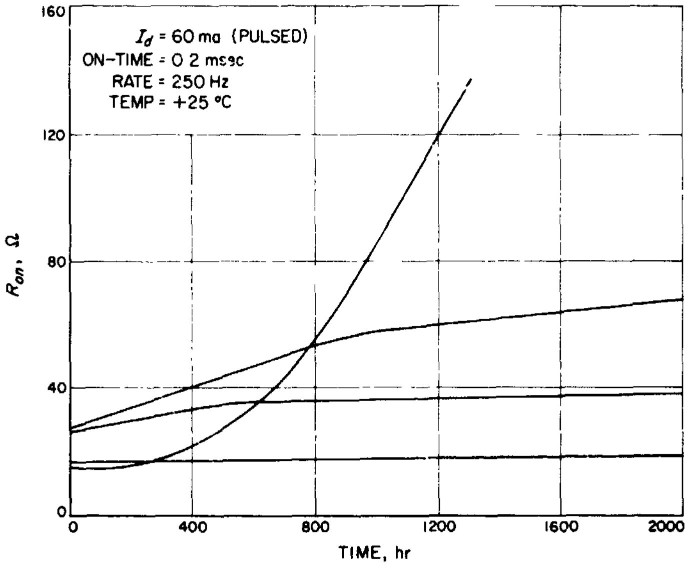

Fig. 2. Graph of on-resistance vs time for several IBM switches

diode with time. This was indicated by a gradual increase in on-resistance. Fig. 2 is a graph of on-resistance vs time for several of these switches. The curves are typical of the different degrees of degradation observed. It is apparent from the different slopes that more than one mode of degradation was occurring. This problem was first observed by IBM near the end of the contract period but was not investigated to any extent. It was theorized that the decrease in photon emission was caused by an increase in surface (leakage) current, which is a nonradiative component of the total current in the diode. Bulk current is the radiative component. It was further theorized that a planar diode would minimize this problem, but IBM did not have a suitable capability for planar diffusion in Ga As at the time.

The IBM contract ended with a successful demonstration of the parameters that could be achieved in a photon actuated switch, together with an indication of a serious degradation mode. The parameters are summarized in Table 1. They are useful parameters for many multiplexing applications. Although IBM packaged the switches in TO-18 cans for handling convenience, it was inferred that they could be packaged in conventional integrated circuit flat packages.

At the time the IBM contract ended, TI was doing a study (Ref. 2) of degradation of light output in Ga As mesa diodes as part of an investigation of optoelectronic phenomena for the Air Force Avionics Laboratory. Two degradation mechanisms had been identified and corrective measures were showing positive results. It was

Table 1. Summary of IBM switch parameters

Parameter	Condition	Value (temp range − 10° to 85°C)
R_{on}	$I_d = 60$ ma (75 mw)	30Ω
R_{off}	$V_{EK} = \pm 5$v	$>10^{8}$Ω
I_{ceo}	$V_{EK} = \pm 5$v	<50 na
$R_{isolation}$	$V_{D\text{-}T} = 35$v	$>10^{11}$Ω
BV_{ce}	$I_{EK} = 100$ μa	>20v
V_{os}	$I_d = 60$ ma	100 μv
t_{on}	$I_d = 60$ ma (pulsed)	<2.5 μsec
t_{off}	$R_L = 10$ kΩ	<10 μsec
C_{ce}	freq = 1.0 kHz	<6 pf

decided to wait until this work was complete before further work was initiated by JPL.

3. The TI Development

In the latter part of 1965 it became apparent that TI had a good handle on the Ga As diode degradation problem. They had corrected the two major degradation mechanisms in mesa diodes, thermally induced stress and increasing surface current, and then they developed a low cost planar process that produced a considerable improvement in stability over their best mesa units. These planar diodes were operated for 1000 hr at 25°C at a bias current density of 1000 amp/cm² with no degradation in light output[1] (Ref. 3). Mainly because of these results it was decided to renew JPL's development of photon isolation circuits. The multiplex switch development was not continued, however, due to the emergence of the MOS transistor as a low level voltage switch. The extremely high input impedance of the MOS provides sufficient isolation of the drive signal for the multiplexing application.

In January 1966, TI was given a contract to develop a photon actuated isolation switch for use at the outputs of a spacecraft command subsystem where complete electrical isolation is necessary for the elimination of DC ground loops. The complete device, shown in Fig. 3, consists of a diode AND gate, a current driver, and a Ga As diode optically coupled to a phototransistor. The gate and driver circuit will be a monolithic integrated circuit. All of these components will be packaged in the ¼ × ⅛ × 1/32-in. TI flat package. The Ga As diode will be glassed to the phototransistor with a SeSAs glass for efficient light coupling. Fig. 4 is a top and side view of the diode-transistor pair.

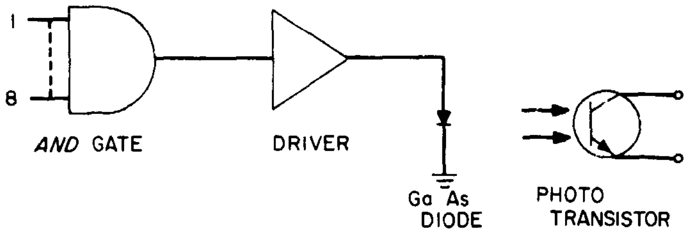

Fig. 3. Diagram of photon-actuated command isolation switch

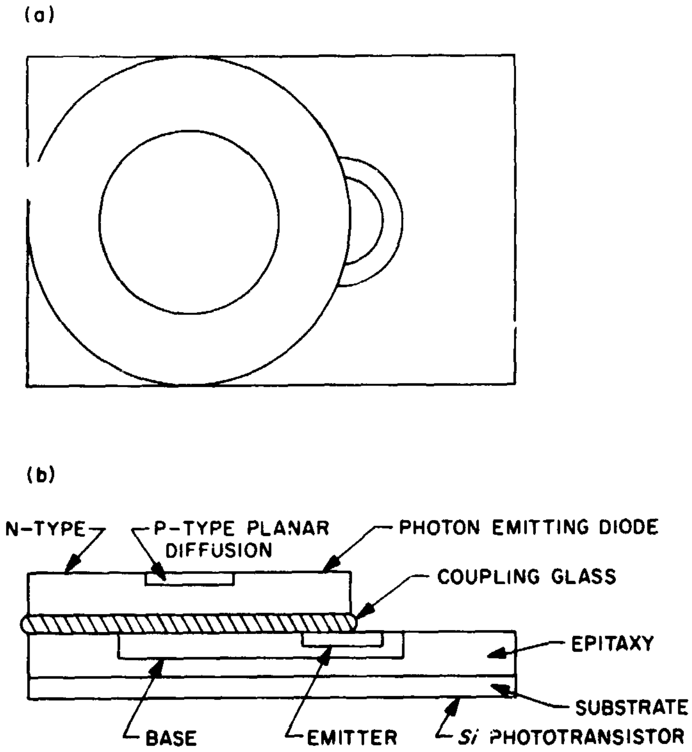

Fig. 4. Diode-transistor pair: (a) top view; (b) side view

The isolation switch is being designed to have the electrical characteristics given in Table 2. The noise transmissibility parameter is a measure of the magnitude of a high speed pulse that will pass through the phototransistor from emitter to collector when it is turned off. Fig. 5 shows the test circuit for this measurement. The other parameters are self explanatory.

Environmental requirements on the isolation switch are: operating temperature range of −20° to +100°C, +150°C storage temperature, thermal and physical shock, vibration, acceleration, and space radiation.

[1]J. R. Biard, "Degradation of Quantum Efficiency in Ga As Light Emitters," 1965 IEEE Solid State Device Research Conference, Princeton, N.J., June 21, 1965.

Table 2. Electrical characteristics

Case temperature (unless specified otherwise); −20 to +100°C					
Parameter	Symbol	Condition	Value		Unit of measure
			Min	Max	
Input voltage:					
At "1" level	V_i		3.0	6.0	v
At "0" level	V_i		0	1.0	v
Input current:					
At "1" level	I_i	$V_i = 6$ v		50	μa
At "0" level	I_i	$V_i = 0.1$ v		−1.0	ma
Output saturation on—voltage	V_{ces}	$V_i = 3.0$ v, $I_c = 10$ ma		0.6	v
Output on—current	I_c	$V_i = 3$ v, $V_{ces} = 0.6$ v	10		ma
Output leakage off—current	I_{ceo}	$V_i = 1$ v, $V_{ce} = 20$ v,			
		Temp = +25°C		0.1	μa
		Temp = +100°C		20	μa
Output breakdown voltage	BV_{ceo}	$V_i = 0$ v, $I_c = 100$ μa	35		v
Isolation capacitance (between output and all other terminals)	C_{iso}	freq = 1.0 kHz		10	pf
Switching times:					
turn on	t_1			10	μsec
turn off	t_2			100	μsec
Noise transmissibility	V_n			2.0	v
Power dissipation:					
Switch on		$V_i = 3$ v, $I_c = 0$		200	mw
Switch off		$V_i = 0$ v, $I_c = 0$		1.0	mw

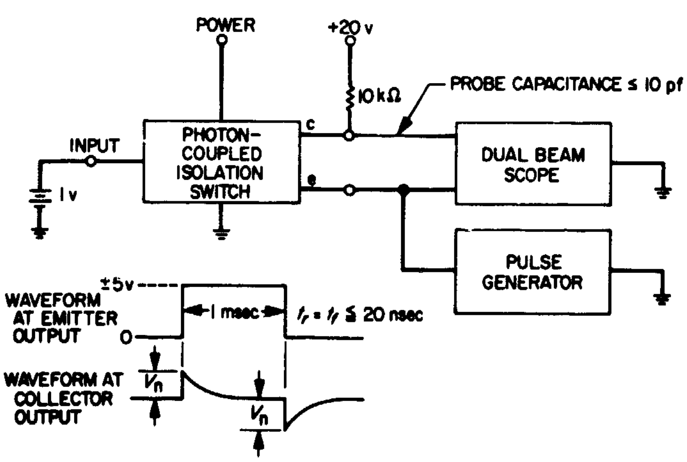

Fig. 5. Noise transmissibility test

The switch development was divided into two parts. Part one consisted of the electrical design of the gate and driver circuit, and the design and fabrication of the diode-transistor combination. Part one has been completed. The results are summarized in the remainder of this report. In the second part of the development the gate and driver circuit will be fabricated as an integrated circuit, and complete isolation switches will be assembled and tested.

When the first diode-transistor pairs were tested the transistor leakage and breakdown characteristics changed drastically with elevated temperature and time. All other parameters were satisfactory. Investigation of the leakage/breakdown problem revealed the cause to be surface inversion in the base and collector regions of the phototransistor. The inversion was caused by charge migration in the coupling glass when a potential is applied between the diode and transistor. The phototransistor was successfully modified to eliminate the collector inversion by addition of a N+ guard ring around the base region and a field relief electrode overlapping the collector-base junction. The base impurity concentration was increased to reduce inversion in that region.

4. Radiation Tests

Early in the development program sample Ga As photon sources, silicon phototransistors, and digital integrated circuits from TI were submitted to an integrated proton irradiation of approximately 1×10^{10} protons/cm^2 at energys of 30, 60, 100 and 140 Mev. The important parameters were measured before and after irradiation, and no significant changes were found. Eleven of the first diode-transistor pairs assembled (Fig. 6) were given another proton irradiation test in which the leakage current of the phototransistor was monitored during irradiation to determine if an "off" transistor would tend to turn on. At flux rates of 4×10^5 protons/cm^2/sec, eight times the maximum rate observed in the most recent period of maximum solar activity (1956–61), leakage current increases of 1 na were seen. This increase is not significant in the intended application. The 11 diode-transistor pairs received a total integrated flux of 2×10^{10} protons/cm^2 during the test, which is equivalent to 1 yr in a deep space trajectory during a period of maximum solar activity. Before and after measurements indicated negligible permanent change in the pair parameters. Later on the pairs will be tested for transient effects due to electron bombardment.

5. Life Test

Following the radiation test the 11 diode-transistor pairs were placed on life test at +25°C. The diode foreward current bias was 50 ma DC on eight of the pairs and zero on the other three pairs. No bias was applied to the phototransistors. After 2500 hr V_{ces} and I_c on some of the biased units had drifted, but none were out of specification. In six

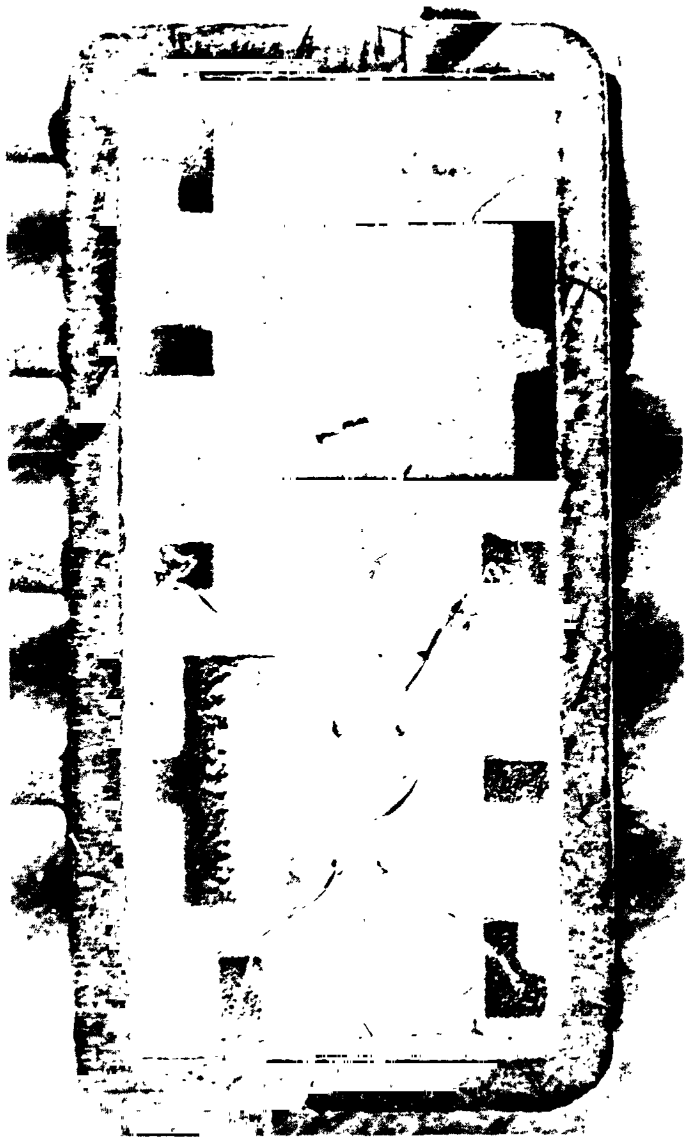

Fig. 6. Diode-transistor pair assembly

of the eight biased units the drift stopped after the first 72 hr, and they remained stable thereafter. The other two biased units continued to drift until the test was stopped at 2500 hr. The three unbiased units did not drift significantly. Considering that the Ga As diodes had not been burned in (operated with bias current for a period of time) and the phototransistors had the inversion problem mentioned above, these results were encouraging. TI is now burning in all their Ga As light sources for 100 hr to stabilize their output.

6. Current Results

Twenty-four diode-transistor pairs with burned in diodes and the modified phototransistors were recently delivered to JPL. Their electrical characteristics are summarized in Table 3. The specified minimum and maximum values are shown with the minimum, average, and maximum measured values for comparison purposes. The average output (collector) current is greater than the input (diode) current indicating a current gain which is greater than unity. Small signal current gain (equivalent to h_{fe} in a transistor) versus collector current is given in Fig. 7 for a typical diode-transistor pair.

Twelve of the 24 units have been on life test for 500 hr with no change in parameters.

The gate and driver circuit has been designed and is presently undergoing final analysis prior to being implemented as an integrated circuit. Fig. 8 is a schematic of the circuit. All of the transistors will have the same area and geometry. In order to handle the maximum diode current of 40 ma, Q2 will be four transistors in parallel.

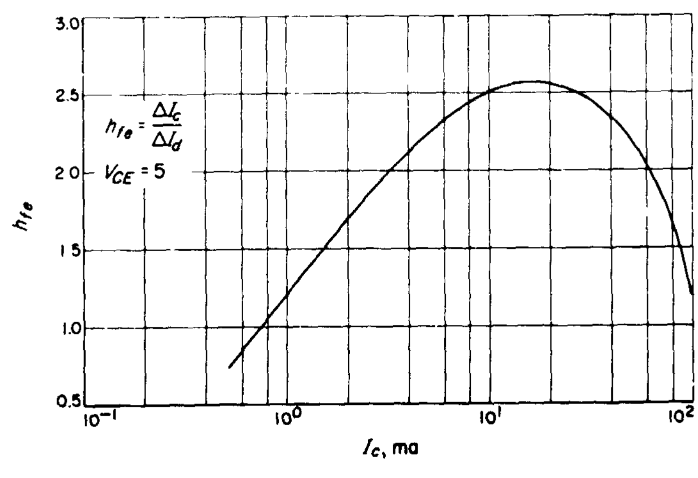

Fig. 7. Current gain of typical diode transistor pair

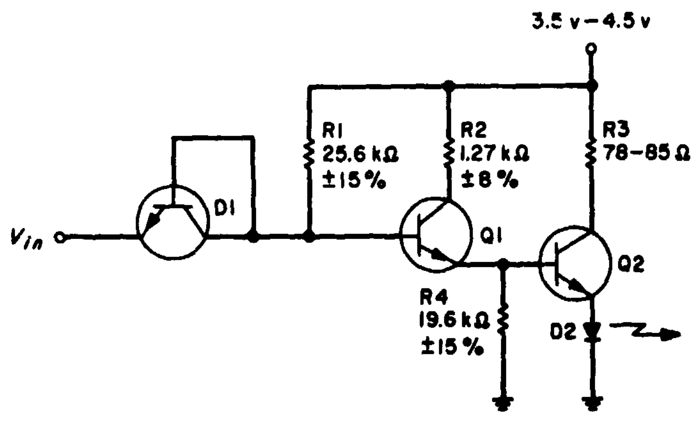

Fig. 8. Gate and driver circuit (one input shown)

Table 3. Electrical characteristics of 24 Ga As diode-Si transistor pairs (Case temperature: +25°C unless specified otherwise)

Parameter	Symbol	Test condition	Specified value		Measured value			Unit of measure
			Min	Max	Min	Ave	Max	
Output saturation on—voltage	V_{CEK}	$I_C = 10$ ma						
		$I_D = 24.5$ ma @ −20°C		0.6	0.08	0.097	0.14	v
		24.0 ma @ +25°C		0.6	0.10	0.122	0.16	v
		22.0 ma @ +100°C		0.6	0.14	0.177	0.24	v
Output on—current	I_C	$V_{CEK} = 0.6$v						
		$I_D = 24.5$ ma @ −20°C	10		18	36.6	48	ma
		24.0 ma @ +25°C	10		20	33.8	45	ma
		22.0 ma @ +100°C	10		16	24.7	32	ma
Output leakage off—current	I_{CKO}	$I_D = 0$, $V_{CK} = +20$v						
		Temperature = +25°C		0.1	0.0001	0.0018	0.0064	μa
		+100°C		20	0.07	5.35	16.0	μa
Output breakdown voltage	BV_{CKO}	$I_D = 0$, $I_C = 100\mu a$						
		Temperature = +25°C	35		52	67.4	90	v
		+100°C	35		48	61.7	85	v
Isolation capacitance (between diode and transistor)	C_{iso}	Frequency = 1.0 kHz		10	1.8	2.6	6.4	pf
Switching times:		$I_D = 20$ ma, $I_C = 10$ ma						
Turn on	t_1			10	2.5	3.35	6.6	μsec
Turn off	t_2			100	17	52.7	72	μsec
Noise transmissibility (emitter to collector)	V_n	$I_D = 0$, $I_C = 2$ ma, $V_i = +5$v		2.0	1.6	—	1.9	v
		−5v		2.0	1.5	—	2.0	v
Diode foreward voltage	V_D	$I_D = 30$ ma			1.203	—	1.256	v

References

1. Bergens, D., *Photon-Actuated Multiplex Switch Development*, Technical Report No. 32-794, NASA Document Number N65-15347, Jet Propulsion Laboratory, Pasadena, California, December 15, 1965.
2. Biard, J. R., *Optoelectronic Functional Electronic Blocks, Interim Report No. 6*, D. D. C. No. AD610871, Texas Instruments, Inc., Dallas, Texas, February 2, 1965.
3. Biard, B., et. al., *Optoelectronic Functional Electronic Blocks*, Technical Report, D. D. C. No. AD802651, Texas Instruments Inc., Dallas, Texas, October, 1966.